Bias-Dependent Luminescence in CdS/CdTe Cells

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ABSTRACT

We observed that external bias V significantly affects the photoluminescence (PL) and drives electroluminescence (EL) in CdTe photovoltaics. PL intensity I(V) increases with the forward bias from V=0 to approximately V_{oc}; for V > V_{oc} I(V) tends to saturate. Reverse bias suppresses I(V). I(V) in the region of forward-bias saturation is extremely sensitive to device stressing. We attribute the observed phenomena to the field-induced separation of the light-generated electrons and holes. At V>V_{oc} the field effect is suppressed so that the PL intensity is dominated by non-radiative recombination. Under forward bias and no illumination, carriers can be injected into the junction and produce EL. We find EL to depend super-quadratically on the injected current. The EL also is very sensitive to stress-induced changes. We have developed a theory that describes important features of the above phenomena more quantitatively.

1. Introduction

One distinctive but little studied feature of photoluminescence in photovoltaics is that both the carrier excitation and radiative recombination leading to PL may occur in the high electric field induced in the junction region. The CdTe/CdS junction is one such example, where the energy gaps of CdTe and CdS are respectively 1.5 eV and 2.5 eV so that the laser beam of the wave length 752 nm is absorbed in the ~ 0.3 μm thick CdTe region adjacent to the CdTe/CdS junction, much narrower than the depletion layer width ~ 1-3 μm.

PL intensity is determined by the partial overlap of the electron and hole distributions separated by the field in the junction provided that the non-radiative recombination is relatively inefficient. In the opposite limiting case, the PL intensity is dominated by the non-radiative recombination before the electrons and holes are spatially separated. By varying the external bias and thus changing the electric field one can observe the crossover between the two regimes and thus characterize the degree of imperfection responsible for nonradiative recombination. From the practical standpoint, observing, under appropriate bias, the crossover between the field- and recombination- dominated PL regimes enables one to detect the presence of defects, which would not show up in the bare built-in field, and thus to characterize the device stability at the earlier stage of its degradation.

2. Experimental

Both the UT made CdTe cells and First Solar cells were used in our experiments. Shown in Fig. 1 are typical data on the bias dependent PL. Some cells (not shown) exhibited the I(V) decreasing with V at considerable

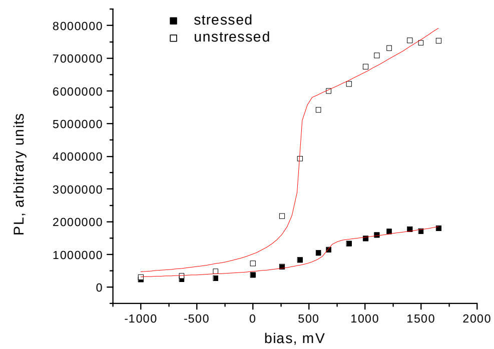

Fig 1. Bias-dependent PL: data (points) under 20-sun laser beam and theoretical fits (curves) by Eq. (2)

forward biases. Note that the observed gigantic degradation effect (by a factor of 5) was achieved in 28 days of light soak and is many orders of magnitude stronger than a typical several percent change in the cell efficiency.

EL was typically observed at V>0.6V. Its spectral dependence was very close to the PL spectral dependence described elsewhere [1]. Fig. 2 shows typical data on the integral EL intensity and corresponding fits by the power dependence $I \propto J^{2+\alpha}$, where J is the electric current density. Typical deviations from the quadratic dependence were characterized by α=0.3-1. Light soak had a profound effect on the EL intensity, analogous to that of the bias dependent PL.

3. Theory

Bias-dependent photoluminescence. The physics behind our bias-dependent PL model (explained in the above) can be described by the steady-state equation for the space distribution of the light-generated electrons and holes that includes generation (g), drift, and recombination

$$g(x) - \mu E \frac{\partial n}{\partial x} - \frac{n}{\tau} = 0, \qquad (1)$$

Here μ and E are the mobility and the electric field, n is the electron (hole) concentration, τ is the recombination lifetime, and the origin is at the metallurgical junction: the

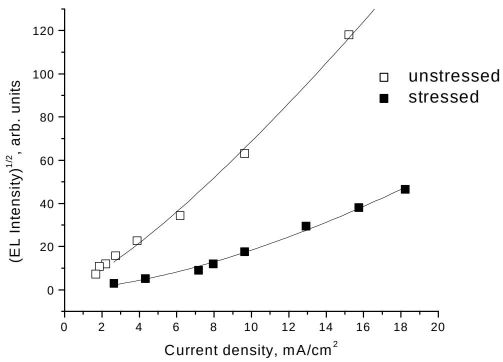

Fig 2. EL intensity as a function of the electric current density: data (points) and theoretical fits (solid lines) with α=0.52 (stressed) and 0.97 (unstressed) in Eq. (3).

regions x>0 and x<0 correspond to CdS and CdTe respectively. The generation rate contains a step-function of coordinate, $g(x) = g_0\Theta(x)\exp(-\alpha x)$.

In Eq. (1) we have assumed: (i) linear recombination kinetics; (ii) uniform electric field; (iii) negligible role of diffusion, justified for the case of practical interest. The boundary conditions to Eq. (1) are that the electron and hole concentrations remain finite everywhere. Solving Eq. (1) and introducing the electron (hole) drift length, $l_{e(h)} = \mu_{e(h)} E \tau_{e(h)}$ the integral PL intensity becomes

$$I \propto \int n_e n_h dx \propto \frac{g_0^2 \tau_e \tau_h}{\alpha(\alpha l_e + 1)(\alpha l_h + 1)} \qquad (2)$$

Eq. (2) predicts indeed that in the limiting case of strong electric fields, $\alpha l_{e(h)} >> 1$, the PL intensity does not depend on the carrier lifetime and strongly depends on the field. In the opposite limiting case of low electric field, $\alpha l_{e(h)} << 1$, the PL intensity does not depend on the field strength, is proportional to the carrier lifetimes and thus depends on the material degradation. When forward bias is strong enough to reverse the field, the above description can be modified by noting that the field will move the electrons and holes in the directions opposite to those in the above.

To compare the above predictions with the experiment we express E in the terms of external bias V. For reverse or moderate forward bias ($V<V_{oc}$), E is determined by the potential drop $V_{oc}-V$ over the depletion length, and thus is proportional to $\sqrt{V_{oc} - V}$. At $V>V_{oc}$ the built-in potential is blocked; hence, the field is almost uniform and proportional to $V-V_{oc}$. As substituted into Eq. (2), so defined electric field led to fits shown in Fig. 1, which are in satisfactory agreement with the data.

Electroluminescence. While the occurrence of EL under considerable forward biases is expected for most semiconductors, its superquadratic current dependence established in the present work requires some explanations. Based on the observed spectra, we believe that the EL is due to the free carrier radiative recombination and thus its intensity depends on the free carrier lifetimes dominated by the trapping processes. The traps are characterized by broad spectra of energies and efficiencies. At high nonequilibrium electron (hole) concentrations $n_{e(h)}$ the most effective traps are clogged. The corresponding trapping lifetime is known to be proportional to some power of the generation rate (number of carriers injected per time, or current) [2]. Therefore we can expect the dependence

$$I \propto J^{2+\alpha} \qquad (3)$$

mentioned in section 1. As is seen from Fig. 2, the latter dependence fits the data rather well. In other words, we relate the observed superquadratic dependence to suppression of trapping efficiencies with electric current. Note that remarkable sensitivity of the observed EL to degradation can be understood along the same lines as that of the bias-dependent PL above: since the built-in electric field is backed up and does not sweep the carriers away, they effectively recombine via the defects accumulated in the course of degradation.

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